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GEOCHEMISTRY AND TECTONIC SETTING OF THE «OPHITES» FROM THE EXTERNAL ZONES OF THE BETIC CORDILLERAS (S. SPAIN)

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ABSTRACT

Mesozoic basic magmatism in the External Zones of the Betic Cordilleras (S. Spain) is represented by small tectonic bodies *(ophites)* in Triassic formations, and submarine flows with abundant pillow-lavas interbedded with Jurassic sediments. Both basic igneous manifestations suffered very low- to low-grade metamorphism, more intense in the case of the *ophites.*

Two types of *ophites* are distinguished on the basis of their primary mineralogy. In the first type, orthopyroxene is present in the less differentiated products. Clinopyroxene and Ca-plagioclase are the main primary phases and quartz appears in the more evolved rocks. In the second type, olivine is present in the less differentiated products. Ti-rich augite and Ca-plagioclase are also important primary minerals, but quartz is absent.

Whole-rock chemistry (major and trace elements, including REE) also allows us to discriminate between these two groups. The first group has higher SiO_2 and lower TiO_2, P_2O_5 and lower Na_2O/K_2O ratios than the second. Normative quartz is almost invariably present in this first group, whereas normative nepheline (lower than 5%) is characteristic of the second group. Both groups are Sr, K, Ba, Rb, Th, Nb and Ce enriched with respect to normal MORB, but the first group has higher K, Rb, Ba, Th and lower Nb, Ce contents than the alkaline group. Nb/Y and Ti/V ratios are also different and show a tholeiitic affinity for the first group and transitional to alkaline for the second. Chondrite-normalised REE patterns in both groups are similar and characterized by LREE enrichment with respect to HREE. LREE/HREE ratios are, however, slightly higher in the transitional to alkaline group.

Various discriminant tectonic diagrams indicate a continental intraplate setting for both *ophite* groups. This magmatism is related to the first extensional period of the Betic Cordilleras, during the Triassic-Jurassic. Geochemical differences between the two groups could evidence different degrees of crustal contamination, and/or different mantle sources. Trace element ratios [$(La/Ce)_n > 1$, $La/Nb < 1.5$] for both magmatism are indicative of an enriched mantle source. Differences in Th/Yb, Zr/Nb, Zr/Y and Ba/Zr ratios underline the greater influence of a lithospheric component in the case of the Triassic magmatism.

Key words: *Ophites; Continental intraplate magmatism; Mesozoic; External Zones; Betic Cordilleras.*

RESUMEN

El magmatismo básico mesozoico en las Zonas Externas de las Cordilleras Béticas (S. España) está representado por pequeños bloques tectónicos *(ofitas)* en las formaciones triásicas, y coladas submarinas, con abundantes pillow-lavas intercaladas en los sedimentos jurásicos. Ambos tipos de manifestaciones ígneas sufrieron transformaciones metamórficas en condiciones de grado bajo a muy bajo, más intensas en el caso de las *ofitas.*

Sobre la base de la mineralogía primaria se han distinguido dos tipos de *ofitas.* En el primer tipo, aparece ortopiroxeno en los términos menos diferenciados, siendo los clino-

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piroxenos y plagioclasas cálcicas las principales fases minerales, con presencia de cuarzo en las rocas más evolucionadas. En el segundo tipo, el olivino está presente en los términos menos diferenciados, siendo también los clinopiroxenos (tipo augita rica en Ti) y las plagioclasas cálcicas las fases minerales más importantes, aunque no existe cuarzo en las rocas más diferenciadas.

Los datos de geoquímica de roca total (elementos mayores y trazas, incluyendo tierras raras) también permiten discriminar entre estos dos grupos. El primero presenta mayores valores de SiO_2 y menores contenidos de TiO_2 y P_2O_5, así como menores relaciones Na_2O/K_2O que el segundo. El primer grupo presenta casi sistemáticamente cuarzo normativo, mientras que el segundo se caracteriza por la presencia de nefelina normativa (< 5%). Ambos grupos están enriquecidos en Sr, K, Ba, Rb, Th, Nb y Ce con respecto a los N-MORB, pero el primer grupo tiene mayores contenidos en K, Rb, Ba y Th y menores valores en Nb y Ce que el segundo. Las relaciones Nb/Y y Ti/V también son diferentes entre los dos grupos, indicando una afinidad toleítica para el primer grupo y transicional-alcalina para el segundo. Los diagramas de tierras raras normalizados a condritos son similares en los dos grupos, y están caracterizados por un enriquecimiento en tierras raras ligeras con respecto a las pesadas, aunque con relaciones ligeramente más altas en el grupo transicional-alcalino.

El uso de varios diagramas de discriminación tectónica indican un contexto de génesis de intraplaca continental para ambos grupos. Este magmatismo está relacionado con los primeros episodios distensivos de las Cordilleras Béticas durante el Triásico-Jurásico. Las diferencias geoquímicas entre los dos grupos podrían indicar distintos grados de contaminación cortical y/o diferente fuente mantélica. Las relaciones entre elementos traza [$(La/Ce)_n > 1$, $La/Nb < 1,5$] en ambos magmatismos son indicativas de una fuente mantélica enriquecida. Las diferencias observadas en las relaciones Th/Yb, Zr/Nb, Zr/Y y Ba/Zr ponen de manifiesto la mayor influencia de un componente litosférico en el caso del magmatismo triásico.

Palabras clave: *Ofitas; Magmatismo de intraplaca continental; Mesozoico; Zonas Externas; Cordilleras Béticas.*

Introduction

Basic rocks of Mesozoic age are present as intercalations in Mesozoic sedimentary formations from the External Zones of the Betic Cordilleras, Southern Spain. Based on the geology of the outcrops and the geochemical data, these rocks can be divided into two types: *a)* subvolcanic rocks emplaced into the Triassic sedimentary units (Trias Keuper), mostly preserved as small tectonic blocks, and classically named as *ophites* in the Spanish geological literature [1]; and *b)* basaltic volcanic rocks (pillow-lavas, sills and locally hyaloclastites) intercalated with the Jurassic sedimentary sequence. This magmatic province, known as the *Jurassic Volcanic Province* (Comas *et al.*, 1986; Puga *et al.*, 1989), is associated with a deep ENE-WSW fault system.

Based on major and trace elements, Puga and Ruiz-Cruz (1980), Comas *et al.* (1986), Puga and Díaz de Federico (1988) and Puga *et al.* (1989) inferred a tholeiitic affinity for the *ophites* and an alkaline-sodic affinity for the basaltic rocks of the *Jurassic Volcanic Province.* Only a few petrological and geochemical studies have been carried out on the *ophites,* due to the relatively small size of the outcrops and the alteration of some of them. Recently, Morata *et al.* (1991), Morata (1993) and Morata and Puga (1993) have studied in detail the mineralogy and geochemistry of the *ophites,* suggesting the tholeiitic affinity of some of these basic rocks, and the more alkalic character of others.

The aim of this paper is to present new geochemical data (major and trace elements, including REE) to demonstrate this duality in the geochemical affinities of the *ophites* from the External Zones of the Betic Cordilleras. A geodynamic framework, based on the mineralogy and the geochemistry, together with radiometric ages, is proposed for this magmatism.

Geological setting and petrography

The Betic Cordilleras, along with the Rif in Northern Morocco, are the westernmost extension of the Mediterranean Alpine chains. The Betic Cordilleras are located in southern and southwestern Spain, and are divided into several major domains: the External and Internal Zones, the Flysch units, and the Neogene basins (fig. 1). The External Zones are located on the southern margin of the Iberian plate.

[1] In this paper the term «ophite» is applied to the small basic igneous bodies present in the Trias Keuper of the External Zones of the Betic Cordilleras, without consideration of their age, outcrop style or geochemical affinity.

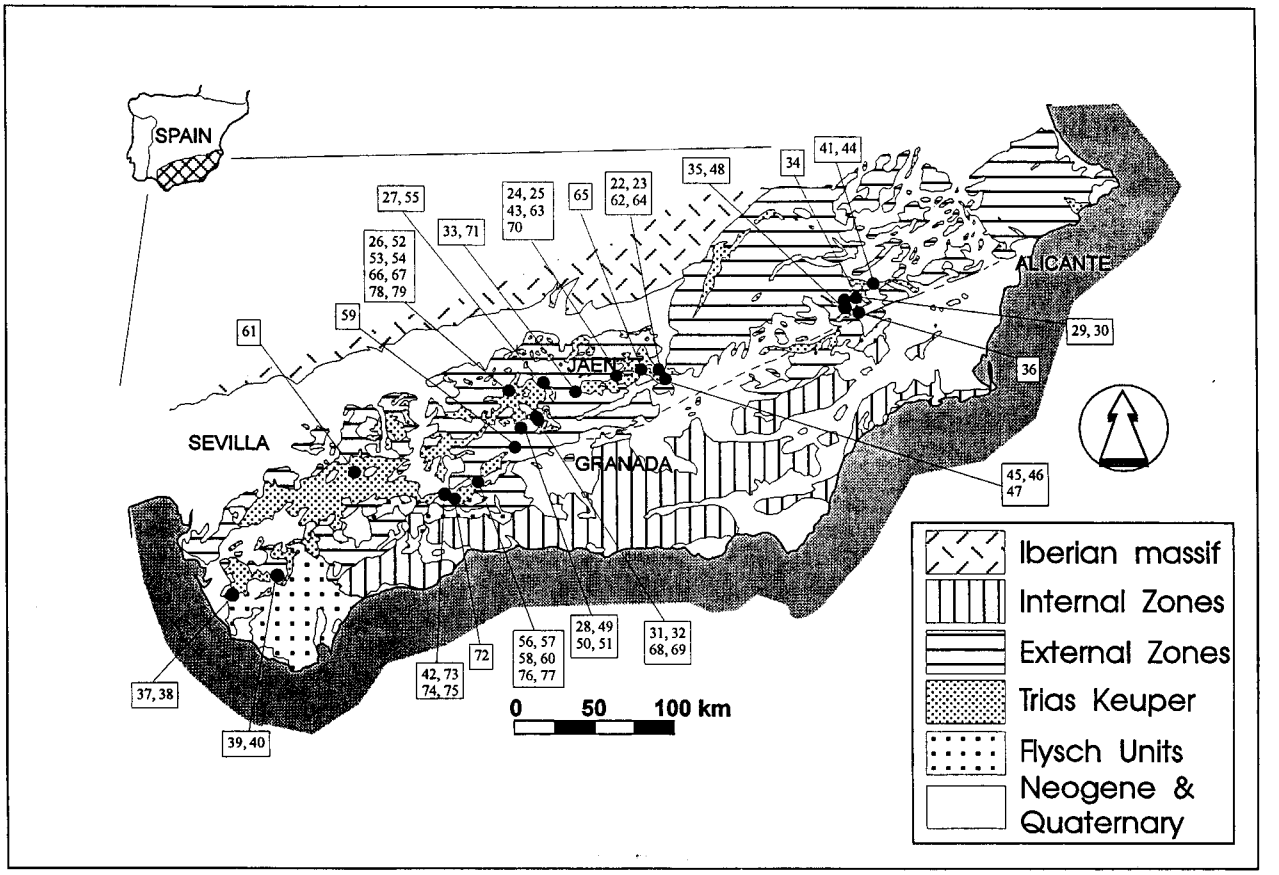

Fig. 1.—Geological map of the Betic Cordilleras (modified from Azema *et al.*, 1979) with the location of the studied outcrops (black dots) and analysed rocks (number of analysed sample in table 1).

They received sediments during the Mesozoic and part of the Cenozoic and were subsequently deformed and detached from the South-Iberian passive margin. Their evolution began during the Triassic, with an extensional episode that continued until the Early-Mid Cretaceous boundary. Significant volumes of volcanic rocks were erupted during this period (see García-Hernández *et al.*, 1980; Sanz de Galdeano, 1993 and references therein). This volcanic activity is represented in two different domains with different outcrop styles. The first domain corresponds to small (several hundred metres), basic igneous bodies *(ophites),* mainly intercalated as tectonic blocks within Triassic evaporitic sediments (Trias Keuper, fig. 1), along a length of *ca.* 500 km. The second domain corresponds to submarine volcanic rocks (pillow-lavas) and sills intercalated with the Jurassic sedimentary rocks. These rocks crop out over an area 200 km long and 5 to 10 km wide, in the central part of the External Zones. Volcanic flows and sills are tenths up to hundred meters thick in some localities.

Petrography and age of the ophites

Three different petrographic facies can be distinguished in the *ophites:* chilled margins, central facies and pegmatoidal differentiated facies. The primary mineralogy is very homogeneous, and only slight variations in the compositions have been found. Clinopyroxene and plagioclase phenocrysts are the main primary phases; however, two groups can be distinguished among the *ophites.* In the first group, orthopyroxene ($Wo_{4.5}En_{75.5}Fs_{20}$ to $Wo_5En_{76}Fs_{19}$) is present in the less differentiated rocks. Calcic plagioclase ($An_{80\text{-}45}$) and calcic clinopyroxene ($Wo_{36}En_{52}Fs_{12}$ to $Wo_{37}En_{39}Fs_{24}$) are the major components. Pigeonite ($Wo_8En_{68}Fs_{24}$ to $Wo_{10}En_{53}Fs_{37}$) appears as a minor phase associated with augite. Quartz is present in the more evolved rocks as single crystals or intergrown with sodic plagioclase. Amphibole (hornblende and Fe-hornblende), biotite, minor apatite and Fe-Ti ores are accessory minerals. The second group is characterized by the presence of olivine ($Fo_{72\text{-}66}$) in the more

Table 1.—**Chemical analyses of the *ophites* from the External Zones of the Betic Cordilleras (major element oxides in weight per cent calculated on an anhydrous basis, and trace elements in ppm). a) Triassic tholeiitic *ophites*. b) Post-Triassic transitional-alkaline *ophites*. *[mg]* values are calculated as $Mg/(Mg+Fe^{2+})$ in atomic proportions, with $Fe^{2+}/Fe^{3+} = 0.15$. b:chilled margins; c = central facies; p = pegmatoidal differentiated facies; p.d. = picritic dolerite. *Q, Hy, Ne,* and *Ol* are normative quartz, hypersthene, nepheline and olivine, respectively.**

Table 1a

Sample	22	23	24	25	26	29	30	34	35	36	37	38	39	40	41	43	44
Facies	c	c	b	b	b	b	c	c	b	c	b	c	b	c	p	c	c
SiO_2	52.97	53.25	52.90	53.22	53.32	53.50	52.60	53.29	54.58	52.61	52.98	53.13	53.02	52.70	53.73	52.59	52.19
TiO_2	1.28	1.19	1.22	1.17	1.14	1.79	1.28	1.20	1.39	1.19	1.30	1.27	1.19	1.07	1.59	1.15	1.05
Al_2O_3	14.06	14.70	14.55	14.71	14.65	13.22	14.62	14.99	17.09	15.06	14.59	14.60	14.58	14.78	13.22	14.55	14.18
Fe_2O_3*	12.63	11.31	11.60	11.54	10.68	14.34	12.08	10.78	8.07	11.30	11.85	11.15	10.40	10.70	13.85	11.49	10.96
MnO	0.23	0.19	0.19	0.18	0.15	0.20	0.19	0.15	0.12	0.18	0.17	0.17	0.16	0.18	0.21	0.19	0.18
MgO	5.69	5.95	6.46	6.41	6.53	4.15	5.50	5.92	4.57	5.82	5.41	5.75	6.20	6.96	5.05	6.43	7.55
CaO	9.64	9.55	8.46	8.44	9.62	7.41	8.51	7.76	8.06	9.47	9.97	10.14	9.33	9.93	9.09	10.27	10.86
Na_2O	2.03	2.38	3.72	2.83	3.11	4.68	3.88	4.78	4.64	3.33	2.99	3.02	4.38	2.65	2.25	2.43	2.20
K_2O	1.31	1.34	0.74	1.36	0.67	0.50	1.19	0.98	1.34	0.91	0.60	0.64	0.59	1.03	0.83	0.75	0.69
P_2O_5	0.16	0.14	0.14	0.13	0.12	0.20	0.14	0.13	0.16	0.13	0.15	0.13	0.13		0.18	0.14	0.13
L.O.I.	1.77	2.70	2.08	2.39	1.47	1.70	1.70	2.85	3.39	1.62	1.23	1.16	1.93	1.54	2.39	1.47	1.00
[mg]	*0.51*	*0.55*	*0.56*	*0.56*	*0.58*	*0.40*	*0.51*	*0.56*	*0.56*	*0.54*	*0.51*	*0.54*	*0.58*	*0.60*	*0.45*	*0.56*	*0.61*
Q	5.61	4.13	0.00	2.21	2.31	0.57	0.00	0.00	0.00	0.35	3.51	3.02	0.00	2.06	8.45	3.22	2.26
Hy	19.95	19.48	19.73	22.51	19.51	16.43	11.25	2.45	8.72	18.40	17.16	16.90	5.21	18.92	19.39	21.03	22.62
Ne	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ol	0.00	0.00	1.34	0.00	0.00	0.00	5.28	12.06	3.28	0.00	0.00	0.00	8.45	0.00	0.00	0.00	0.00
Ba	304	179	201	280	315	202	264	164	557	217	162	177	159	203	173	206	173
Rb	45	34	22	40	25	15	40	24	37	32	24	24	23	53	22	24	25
Th	2.7	2.7	2.3	2.4	2.0	3.6	2.5	2.3	2.8	2.4	2.4	2.5	2.0	2.0	3.1	2.3	2.0
Nb	12	10		18	17	19	16	18	15	16	17	19	18	16	6	7	9
Sr	255	298	139	200	200	316	391	690	722	305	204	220	278	228	226	225	239
Zr	93	74	111	92	110	181	125	110	114	99	115	113	114	93	145	100	91
Y	22	22	17	24	22	40	40	33	15	17	25	24	15		26	21	19
Cr	86	150	149	206	263	16	66	150	183	120	75	120	195	322	57	200	370
V	320	300	294	291	293	382	321	309	312	280	308	279	290	266	364	319	260
Ni	71	68	55	67	65	34	60	62	75	58	51	56	62	76	39	63	84
Co	41	41	50	46	43	50	51	48	42	46	44	46	40	45	59	65	70
Sc			30.7	28.7	31.8	32.5	34.6	33.5	39.0	32.0	31.3	33.5	32.9	12.2	33.4	32.8	33.8
Cu	180	120	121	115	88	150	128	75	102	104	132	92	41	94	176	117	109
Zn	320	100	68	71	66	105	93	108	76	809	79	70	49	88	101	82	84
Li	10	20	37	30	26	19	28	56	20	21	10	12	40	30	17	19	12
Hf	3.0	3.0	3.2	2.8	2.8	4.0	2.9	3.1	3.7	3.0	3.0	3.0	2.9	2.7	4.0	3.1	3.1
U	0.6	0.9	0.5	0.5	0.6	0.8	0.5	<0.5	<0.5	0.6	0.5	0.6	0.6	0.5	1.1	0.4	0.5
Tb	0.8	0.7	0.8	0.7	0.7	1.0	0.8	0.7	0.7	0.7	0.8	0.7	0.8	0.6	0.9	0.7	0.6
La	14.80	13.70	13.60	13.30	11.90	19.00	13.80	12.40	11.00	12.20	13.80	12.70	11.80	10.10	11.30	11.60	10.60
Ce	31.80	29.10	27.60	29.10	25.90	40.50	30.10	26.50	25.10	25.30	31.90	28.30	26.40	23.70	35.40	24.80	22.60
Nd	16.20	14.40	18.90	17.10	15.90	25.10	18.20	16.10	15.70	16.40	18.30	17.30	16.00	14.30	20.90	14.80	12.90
Sm	4.00	3.70	4.20	4.00	3.60	5.70	4.30	3.80	4.00	3.70	4.50	4.10	4.10	3.30	5.10	3.90	3.40
Eu	1.67	1.41	1.45	1.26	1.24	1.79	1.39	1.27	1.34	1.24	1.40	1.25	1.21	1.11	1.62	1.15	1.02
Gd	4.60	4.10	4.70	4.20	4.20	6.40	4.70	4.20	4.20	4.20	4.70	4.80	4.50	3.90	5.50	3.90	360
Tb	0,80	0.70	0.80	0.70	0.70	1.00	0.80	0.70	0.70	0.70	0.80	0.70	0.80	0.60	0.90	0.70	0.60
Dy	4.50	4.00	4.80	4.70	4.40	6.70	4.80	4.50	4.40	4.60	4.90	4.80	4.80	4.10	5.10	4.00	3.80
Ho	0.96	0.87	1.01	0.95	0.90	1.33	1.00	0.92	0.86	0.88	1.02	0.97	0.95	0.80	1.05	0.89	0.77
Er	2.70	2.40	2.80	2.60	2.40	3.90	2.70	2.60	2.50	2.50	2.90	2.80	2.70	2.40	2.60	2.50	2.30
Yb	2.50	2.50	2.60	2.30	2.30	3.70	2.60	2.40	2.20	2.20	2.90	2.40	2.50	2.10	2.20	2.20	1.90
Lu	0.34	0.29	0.38	0.37	0.35	0.54	0.43	0.33	0.31	0.30	0.43	0.36	0.37	0.32	0.34	0.34	030

primitive rocks. Calcic plagioclase (An_{70-50}) and pinkish Ti-rich augite ($Wo_{46}En_{39}Fs_{15}$ to $Wo_{47}En_{31}Fs_{22}$), are associated in ophitic texture. Ti-rich amphibole, phlogopitic biotite, apatite and Fe-Ti ores are accessory phases. Quartz is absent.

All these basic igneous rocks have been affected by very low- to low-grade metamorphism, giving secondary assemblages in the prehnite-actinolite, prehnite-pumpellyite and pumpellyite-actinolite facies (Puga *et al.*, 1983; Morata, 1993; Morata *et al.*, 1992, 1994). The metamorphic minerals partly replace the primary phases, although the primary igneous textures are always preserved. This replacement can be complete, except for clinopyroxene, which is preserved as a relic mineral. Clinopyroxenes are completely replaced by metamorphic assemblages only in some metabasites, in which metamorphic Na-pyroxene and metamorphic Na-amphibole are present (Morten and Puga, 1983; Morata *et al.*, 1994).

Table 1 (cont.)—**Chemical analyses of the *ophites* from the External Zones of the Betic Cordilleras (major element oxides in weight per cent calculated on an anhydrous basis, and trace elements in ppm). a) Triassic tholeiitic *ophites*. b) Post-Triassic transitional-alkaline *ophites*. *[mg]* values are calculated as Mg/(Mg+Fe^{2+}) in atomic proportions, with Fe^{2+}/Fe^{3+} = 0.15. b:chilled margins; c = central facies; p = pegmatoidal differentiated facies; p.d. = picritic dolerite. *Q, Hy, Ne,* and *Ol* are normative quartz, hypersthene, nepheline and olivine, respectively.**

Table 1a (cont.)

Sample	48	52	53	54	61	62	63	64	65	66	67	70	73	74	75	78	79
Facies	b	c	p	b	c	c	b	c	c	c	b	c	c	c	c	b	p
SiO_2	52.37	52.34	53.43	52.54	52.67	52.47	53.44	52.77	52.72	52.33	52.40	51.22	52.15	53.01	53.16	51.17	51.47
TiO_2	1.14	1.19	2.15	1.15	1.29	1.22	2.02	1.26	1.35	1.11	1.18	1.17	1.43	1.41	1.09	1.20	2.15
Al_2O_3	14.48	14.32	12.38	14.27	14.36	14.57	13.44	14.67	14.26	14.81	14.23	15.27	15.85	14.56	14.79	15.02	13.59
Fe_2O_3*	11.26	11.70	16.30	11.45	12.22	11.92	14.45	12.12	12.00	11.35	10.73	11.50	11.00	10.02	9.33	11.79	16.66
MnO	0.17	0.18	0.23	0.18	0.22	0.24	0.25	0.19	0.18	0.17	0.16	0.18	0.16	0.16	0.18	0.17	0.22
MgO	6.49	6.57	3.53	7.00	5.83	6.41	3.78	5.83	5.72	5.85	6.29	6.67	6.02	6.17	7.42	7.00	3.68
CaO	10.55	10.29	7.95	9.46	9.06	7.73	5.12	9.19	9.07	10.08	9.00	10.19	7.39	8.32	8.74	9.75	8.17
Na_2O	2.65	2.62	2.56	2.28	2.78	2.69	6.15	2.60	3.68	3.18	5.01	2.88	4.22	5.36	2.85	3.04	2.70
K_2O	0.74	0.65	1.22	1.53	1.40	2.59	1.08	1.21	0.84	0.93	0.82	0.71	1.56	0.77	2.27	0.72	1.15
P_2O_5	0.14	0.15	0.26	0.14	0.16	0.15	0.27	0.16	0.17	0.19	0.17	0.20	0.21	0.21	0.17	0.12	0.22
L.O.I.	0.77	0.77	0.54	0.77	1.77	1.85	1.00	2.23	1.93	1.40	1.88	2.96	4.27	2.89	3.29	3.06	1.94
[mg]	*0.57*	*0.56*	*0.33*	*0.58*	*0.52*	*0.55*	*0.37*	*0.52*	*0.52*	*0.54*	*0.57*	*0.57*	*0.55*	*0.58*	*0.64*	*0.58*	*0.33*
Q	1.72	2.22	8.12	1.62	1.51	0.00	0.00	2.84	0.00	0.80	0.00	0.00	0.00	0.00	0.00	1.29	7.57
Hy	19.84	21.11	18.83	23.32	20.93	18.06	0.00	21.44	16.66	16.42	0.00	19.82	7.04	0.00	17.95	17.29	13.69
Ne	0.00	0.00	0.00	0.00	0.00	0.00	1.52	0.00	0.00	0.00	2.02	0.00	0.00	1.41	0.00	0.00	0.00
Ol	0.00	0.00	0.00	0.00	0.00	4.45	13.43	0.00	1.79	0.00	8.63	1.02	7.89	8.26	1.24	0.00	0.00
Ba	223	197	275	250	307	422	198	260	198	180	213	149	84	62	211	256	315
Rb	26	21	38	39	34	56	23	37	23	20	15	14	33	17	61	18	35
Th	2.2	2.2	4.5	2.7	2.6	2.2	5.1	2.0	2.5								
Nb	10	8	14	8	8	8	11	9	8	8	11	10	11	12	9	5	15
Sr	225	235	227	262	208	310	201	233	510	228	346	197	164	145	191	340	261
Zr	103	100	167	103	117	105	188	108	115	104	103	100	118	122	92	89	174
Y	21	21	37	22	23	21	36	21	23	25	26	24	29	32	23	24	43
Cr	180	170	16	260	110	150	45	80	77	127	180	199	101	220	433	279	17
V	279	252	349	283	289	216	293	247	278	275	275	262	285	279	257	268	362
Ni	65	57	16	65	46	53	31	47	44	73	81	75	56	63	86	88	38
Co	60	58	81	69	52	49	42	50	52	57	58	48	33	36	39	48	74
Sc	33.9	33.4	34.6	34.5	32.3	31.3	34.7	31.3	32.7								
Cu	113	108	172	108	130	122	158	124	73	120	66	113	40	13	62	106	164
Zn	86	74	113	79	110	187	34	91	72	106	65	85	85	76	85	74	115
Li	10	9	16	21	24	36	6	10	13	17	20	21	66	48	43	22	15
Hf	2.8	3.2	5.6	3.2	2.6	2.9	5.5	3.2	3.3								
U	0.3	0.5	1.0	0.7	0.7	0.6	1.1	0.5	0.4								
Tb	0.7	0.7	1.1	0.6	0.7	0.7	1.1	0.7	0.8								
La	11.80	11.30	21.70	11.70	13.20	12.50	18.80	12.40	13.90	14.30	15.30	11.40	16.50	17.80	8.66	11.70	24.10
Ce	24.20	23.90	44.20	24.20	27.40	26.00	40.30	26.50	29.30	29.50	29.20	25.60	32.70	44.90	21.10	27.40	53.70
Nd	14.70	15.00	26.50	13.10	15.80	14.80	23.00	16.80	16.40	15.60	16.90	13.90	17.40	21.80	10.90	13.10	26.10
Sm	3.50	3.20	6.10	3.20	3.70	3.60	6.00	4.30	4.20	3.70	3.77	3.35	4.03	4.82	2.64	3.23	5.88
Eu	1.13	1.24	1.94	1.07	1.34	1.27	1.65	1.43	1.27	1.24	1.21	1.13	1.28	1.35	0.85	1.10	1.80
Gd	4.10	4.10	6.80	3.40	4.10	4.00	6.40	4.50	4.40	3.78	3.86	3.52	4.09	4.32	2.84	3.42	6.45
Tb	0.70	0.70	1.10	0.60	0.70	0.70	1.10	0.70	0.80								
Dy	4.20	4.40	7.10	4.10	4.60	4.40	6.50	4.40	4.80	4.16	4.41	4.09	4.35	4.66	3.14	3.91	7.26
Ho	0.88	0.84	1.45	0.80	0.93	0.89	1.39	0.90	0.97								
Er	2.30	2.50	4.10	2.40	2.70	2.50	3.80	2.40	2.80								
Yb	2.20	2.00	3.50	2.30	2.30	2.40	3.20	1.90	2.40	2.12	2.22	2.10	1.98	1.92	1.50	2.06	3.69
Lu	0.35	0.32	0.54	0.36	0.37	0.36	0.50	0.33	0.34	0.33	0.37	0.35	0.38	0.30	0.25	0.34	0.67

* all iron as Fe_2O_3.

Radiometric age determinations (K/Ar method) and field relations (Morata, 1993; Portugal-Ferreira *et al.*, 1995) have shown that the orthopyroxene bearing *ophites* are Late Triassic in age (182 ± 9 to 187 ± 4), while the olivine bearing *ophites* are post-Triassic, and probably Jurassic (137 ± 4). Therefore the two groups of *ophites* present in the Triassic sedimentary rocks of the External Zones of the Betic Cordilleras can be distinguished from mineralogy, radiometric ages and field relations as: (1) Triassic *ophites*, and (2) post-Triassic *ophites*.

Geochemistry

The new chemical data set presented in this paper (table 1) was obtained in the X-Ray Assay Labora-

Table 1 (cont.)—**Chemical analyses of the *ophites* from the External Zones of the Betic Cordilleras (major element oxides in weight per cent calculated on an anhydrous basis, and trace elements in ppm). a) Triassic tholeiitic *ophites*. b) Post-Triassic transitional-alkaline *ophites*. *[mg]* values are calculated as $Mg/(Mg+Fe^{2+})$ in atomic proportions, with $Fe^{2+}/Fe^{3+} = 0.15$. b:chilled margins; c = central facies; p = pegmatoidal differentiated facies; p.d. = picritic dolerite. *Q, Hy, Ne,* and *Ol* are normative quartz, hypersthene, nepheline and olivine, respectively.**

Table 1b

Sample	27	28	31	32	33	42	45	46	47	49	50	51	55	56	57	58	59
Facies	p	p.d.	b	p	b	c	b	c	p	c	c	c	p	c	c	c	b
SiO_2	51.49	45.37	49.44	52.79	49.93	48.22	50.21	47.67	49.95	48.33	49.33	47.81	52.41	49.74	49.28	47.32	47.75
TiO_2	2.32	1.18	2.11	2.21	2.52	2.28	1.72	1.26	3.60	1.82	1.65	1.75	2.30	2.81	2.40	2.74	1.76
Al_2O_3	16.20	11.19	18.25	16.22	16.37	17.72	16.91	16.20	14.05	17.28	16.61	16.63	15.44	16.61	17.01	13.96	17.55
Fe_2O_3*	8.60	13.38	11.52	10.13	12.43	11.75	11.20	11.14	12.84	12.34	11.73	10.64	13.10	11.87	11.93	13.85	11.49
MnO	0.21	0.19	0.08	0.11	0.17	0.18	0.24	0.17	0.19	0.13	0.22	0.17	0.21	0.11	0.15	0.24	0.19
MgO	5.53	19.86	7.82	2.45	5.21	6.67	6.79	10.63	4.04	4.45	9.12	7.85	2.18	5.88	6.11	10.06	6.59
CaO	9.47	6.29	4.61	8.72	7.70	7.30	6.26	9.42	9.47	10.80	6.01	11.36	5.47	6.42	6.98	6.69	9.37
Na_2O	4.21	1.71	3.12	6.00	4.53	3.85	2.29	2.52	4.54	3.82	3.49	3.17	4.71	5.48	5.06	3.61	3.19
K_2O	1.62	0.64	2.80	1.10	0.69	1.56	4.16	0.83	0.92	0.67	1.63	0.43	3.50	0.58	0.60	0.99	1.78
P_2O_5	0.35	0.18	0.26	0.28	0.47	0.48	0.21	0.17	0.38	0.36	0.21	0.21	0.67	0.51	0.48	0.54	0.33
L.O.I.	3.16	3.77	8.39	8.16	3.62	3.08	2.00	2.31	1.23	2.39	3.00	3.39	1.23	2.70	3.08	3.00	2.62
[mg]	*0.59*	*0.77*	*0.61*	*0.36*	*0.49*	*0.56*	*0.58*	*0.68*	*0.42*	*0.45*	*0.64*	*0.63*	*0.28*	*0.53*	*0.54*	*0.62*	*0.57*
Q	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hy	0.00	10.40	11.86	0.00	2.29	0.00	3.54	3.50	0.00	0.00	4.16	0.00	0.00	0.00	0.00	0.44	0.00
Ne	2.00	0.00	0.00	6.12	0.00	1.75	0.00	0.00	1.99	2.94	0.00	2.16	2.11	3.12	2.84	0.00	3.36
Ol	9.14	41.85	15.20	2.85	13.15	20.35	18.37	24.18	7.16	11.37	24.22	16.69	10.18	17.21	18.22	27.54	17.63
Ba	173	167	265	160	116	428	1,500	108	102	136	483	73	446	76	75	82	186
Rb	28	23	60	19	12	15	90	18	20	16	32	12	53	14	11	16	22
Th	2.7	1.4	1.5	3.2	2.7	1.6	1.3	1.0	2.5	3.3	1.1	1.4	4.9	0.9	1.1	1.5	1.9
Nb	28	22	21	33	57	15	11	8	21	27	12	14	36	17	17	18	22
Sr	434	304	247	94	445	299	1,510	386	405	289	597	231	660	475	436	135	425
Zr	181	84	124	144	215	199	104	90	182	131	116	107	297	235	217	243	122
Y	46	12	20	9	20	29	23	16	38	24	23	19	40	35	32	38	22
Cr	162	795	289	81	80	39	300	220	54	130	280	220	7	130	160	130	160
V	243	146	229	164	232	222	204	152	252	198	190	204	153	260	270	225	215
Ni	32	596	106	26	39	83	51	106	9	19	151	74	12	65	72	176	47
Co	44	81	44	38	47	54	50	64	65	52	63	45	40	52	60	73	51
Sc	26.4	14.5	26.5	19.3	23.8	12.1	28.3	22.3	49.0	25.8	28.0	26.7	20.7	27.4	26.8	24.9	27.4
Cu	24	86	73	16	54	26	28	54	24	45	60	20	20	3	17	7	62
Zn	38	81	137	49	77	99	85	82	44	66	68	44	67	71	88	111	106
Li	34	16	148	26	48	44	102	35	22	61	54	29	17	45	50	40	88
Hf	4.4	1.9	3.0	3.6	4.6	5.3	3.4	2.7	5.0	3.8	3.5	2.3	7.8	6.0	5.3	5.5	3.0
U	0.9	0.3	0.5	0.8	0.8	0.3	0.2	0.3	0.5	0.9	0.3	1.0	1.6	0.6	0.3	0.6	0.5
Tb	1.1	0.5	0.7	0.8	1.3	1.0	0.7	0.8	1.2	0.8	0.6	0.6	1.4	1.2	1.1	1.2	0.7
La	19.00	10.20	13.50	18.20	24.30	14.40	9.40	8.30	18.20	33.00	8.80	11.90	38.50	16.50	15.30	15.90	14.60
Ce	40.90	20.50	29.00	37.70	53.00	33.60	20.50	17.70	41.00	56.40	18.80	23.40	75.00	38.90	36.20	38.80	30.00
Nd	24.70	11.30	17.20	21.10	30.60	22.50	13.00	11.00	24.40	23.00	11.50	13.60	39.70	25.50	23.20	25.60	16.30
Sm	5.80	2.50	4.00	4.80	6.70	5.40	3.60	2.80	6.00	4.30	3.00	3.00	8.80	6.50	6.10	6.30	3.50
Eu	2.05	0.92	1.60	1.67	2.27	1.83	1.31	1.06	1.92	1.60	1.12	1.26	2.17	2.31	2.04	1.98	1.25
Gd	6.10	2.80	4.50	5.10	7.30	5.90	4.20	3.00	7.40	5.00	3.70	3.70	8.70	7.10	7.00	6.50	4.50
Tb	1.10	0.50	0.70	0.80	1.30	1.00	0.70	0.50	1.20	0.80	0.60	0.60	1.40	1.20	1.10	1.20	0.70
Dy	6.20	3.10	4.30	4.40	7.60	6.20	4.80	3.00	7.70	5.20	4.10	3.90	8.40	7.40	6.80	7.40	4.40
Ho	1.16	0.60	0.77	0.80	1.48	1.17	0.89	0.62	1.45	0.97	0.88	0.78	1.64	1.39	1.29	1.50	0.85
Er	3.10	1.70	2.00	1.90	4.10	3.40	2.60	1.80	4.10	2.50	2.50	2.30	4.50	3.80	3.50	4.10	2.60
Yb	2.70	1.50	1.60	1.40	3.70	2.80	2.10	1.50	3.40	2.20	2.30	1.80	3.60	2.70	2.20	3.80	2.10
Lu	0.39	0.24	0.27	0.19	0.48	0.43	0.31	0.23	0.54	0.36	0.36	0.28	0.56	0.35	0.32	0.56	0.34

tories (Canada) (analyses 22 to 65) using XRF for Si, Ti, Al, Fe, Mg, Ca, Ba, Rb, Nb, Sr and Zr; ICP for Mn, P, Y, Ni, Co, Sc, Pb, Cu, Zn and Li; NA for Th, Cr, Ta, Hf, and U; AA for Na and K; DCP for V and ICP-MS for REE, and in the Laboratoire de Pétrologie Magmatique, Université d'Aix-Marseille III (France) (analyses 66 to 79), using AA for Mn, Na, K, Rb, Nb, Sr, Y, Cr, V, Ni, Pb and Cu, and ICP for Si, Ti, Al, Fe, Mg, Ca, P, Ba, and REE. With the aim to check the two analytical laboratories, double analyses of two samples were carried out, showing a relatively good concordance. Previous chemical analyses in Puga *et al.* (1989) have been reinterpreted based on the two groups here defined.

Whole rock chemistry

Almost all the Triassic *ophites* are hypersthene normative, and some of them are oversaturated in

Table 1 (cont.)—**Chemical analyses of the *ophites* from the External Zones of the Betic Cordilleras (major element oxides in weight per cent calculated on an anhydrous basis, and trace elements in ppm). a) Triassic tholeiitic *ophites*. b) Post-Triassic transitional-alkaline *ophites*. *[mg]* values are calculated as Mg/(Mg+Fe^{2+}) in atomic proportions, with Fe^{2+}/Fe^{3+} = 0.15. b:chilled margins; c = central facies; p = pegmatoidal differentiated facies; p.d. = picritic dolerite. *Q, Hy, Ne,* and *Ol* are normative quartz, hypersthene, nepheline and olivine, respectively.**

Table 1b (cont.)

Sample	60	68	69	71	72	76	77
Facies	c	b	p	b	c	c	p
SiO_2	48.02	49.51	48.22	49.97	50.20	49.32	49.16
TiO_2	2.29	1.97	2.12	1.88	1.35	2.85	2.94
Al_2O_3	16.77	18.10	15.11	18.29	17.20	16.04	16.49
Fe_2O_3*	11.15	12.03	12.74	10.34	11.12	12.98	13.71
MnO	0.17	0.08	0.14	0.29	0.19	0.10	0.09
MgO	8.00	8.41	1.38	6.16	8.22	6.13	6.97
CaO	8.11	2.90	12.35	6.94	4.99	5.77	3.42
Na_2O	3.02	4.16	6.21	4.10	3.49	6.27	5.86
K_2O	2.11	2.54	1.14	1.76	3.05	0.18	0.97
P_2O_5	0.35	0.30	0.57	0.26	0.19	0.36	0.39
L.O.I.	3.08	6.84	9.17	5.09	4.48	3.63	4.12
[mg]	*0.62*	*0.61*	*0.20*	*0.58*	*0.53*	*0.62*	*0.54*
Q	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hy	0.00	15.30	0.00	0.00	1.92	0.00	0.00
Ne	1.53	0.00	10.59	0.15	0.00	3.22	0.83
Ol	20.98	6.71	0.00	15.60	20.43	10.14	16.80
Ba	209	162	112	154	61	19	29
Rb	27	23	11	26	46	5	15
Th	0.8						
Nb	12	18	37	6	7	8	16
Sr	344	171	178	485	143	413	111
Zr	159	123	211	147	60	204	226
Y	60	27	41	30	18	37	49
Cr	170	266	16	248	373	133	111
V	227	205	148	201	181	298	302
Ni	117	95	19	59	119	69	71
Co	54	42	27	32	30	48	68
Sc	25.5						
Cu	7	58	48	39	84	9	10
Zn	85	118	35	142	106	75	69
Li	45	100	62	61	62	44	50
Hf	3.7						
U	0.3						
Tb	0.8						
La	10.20	14.70	25.50	14.60	12.00	17.70	17.10
Ce	24.80	30.10	53.30	31.90	27.30	38.30	41.40
Nd	17.20	16.60	27.60	16.30	14.70	22.40	23.10
Sm	4.50	4.22	6.85	3.96	3.60	5.70	5.97
Eu	1.65	1.57	2.00	1.37	1.38	2.29	2.17
Gd	5.20	4.41	7.13	4.19	3.75	6.22	7.06
Tb	0.80						
Dy	5.10	4.60	6.77	4.52	3.86	6.40	7.95
Ho	1.10						
Er	2.90						
Yb	2.30	1.70	2.40	2.17	1.43	2.12	2.52
Lu	0.34	0.27	0.35	0.35	0.24	0.32	0.35

* all iron as Fe_2O_3.

silica (normative quartz; table 1). This is consistent with the mineralogy of these *ophites*. Most of the rocks from the post-Triassic *ophites* are, on the opposite, nepheline normative (always less than 5%).

In spite of their relatively high loss-on-ignition contents (L.O.I. is usually higher than 2%), we have used the recommended TAS diagram to classify the basic rocks (fig. 2). Based on their SiO_2 and alkaline contents, the Triassic *ophites* are mostly basaltic andesite and plot in the quartz-normative field, while the post-Triassic rocks are mostly hawaiite or basalt, and plot between the hypersthene and nepheline-normative fields (fig. 2). The main differences between the two groups are related to the SiO_2 content, generally higher in the Triassic rocks, while post-Triassic rocks show major variations in SiO_2 (see fig. 2 and table 1). The rock close to 45 wt% SiO_2 (sample n.° 28) belonging to the post-Triassic magmatism corresponds to a picritic dolerite. In each group, the pegmatoidal differentiated rocks have the higher SiO_2 values. The wide range in alkalies observed in both groups may be partially a consequence of the mobility of these elements during secondary processes.

The Na_2O/K_2O ratios are different in the Triassic (mean value of 3.6, range 9.4 to 1.0) and the post-Triassic *ophites* (mean value of 7.6, range 33.9 to 0.6). In spite of the alkali mobility during secondary processes, differences in the Na_2O/K_2O ratio must be probably be related to a primary feature, with higher Na_2O/K_2O values in the post-Triassic magmatism. Differences in the L.O.I. values are also apparent: the mean value is 2.08% (ranging between 5.97 to 0.54%) for the Triassic rocks, and it is higher (4.02%, ranging between 9.17 and 1.29%) for the post-Triassic group.

Major element variations with respect to *[mg]* values (*[mg]* = Mg/(Mg+Fe^{2+}) in atomic proportions, with Fe^{2+}/Fe^{3+} = 0.15), taken as differentiation index, are shown in figure 3. The *[mg]* values are in the range 0.3-0.7; the 0.7 value belongs to a picritic dolerite, with 20% MgO, whereas *[mg]* values lower than 0.3 correspond to the pegmatoidal differentiated facies. The scattered plots of CaO, Na_2O and K_2O reflect the high mobility of these elements during secondary processes. In spite of Ca mobility, a positive rough correlation is observed with *[mg]* for the Triassic rocks. Higher Na_2O values in some chilled margins can be a consequence of local interaction with the host Triassic evaporitic sediments. In fact, field evidences in some outcrops, as well as the presence of scapolite in others (Morata *et al.*, 1996), confirm such an interaction with these evaporitic sediments. TiO_2 and P_2O_5, contents are higher in the post-Triassic (1 to 3% and 0.3 to 0.6%, respectively) than in the Triassic *ophi-*

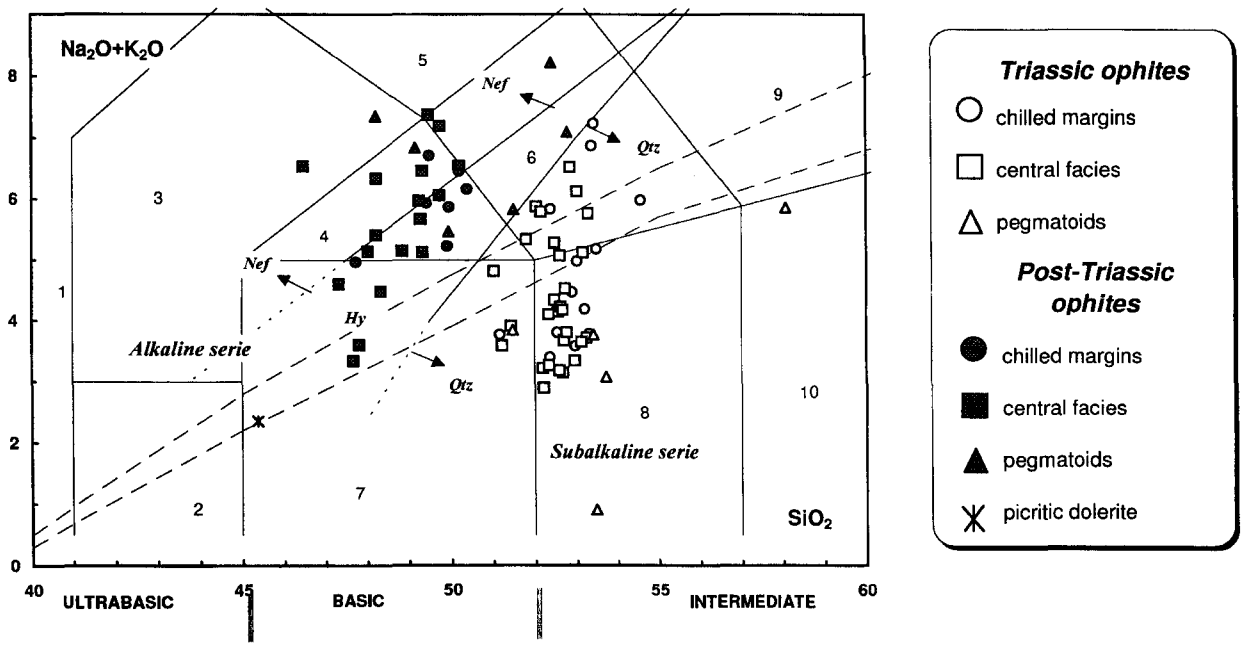

Fig. 2.—Total alkali versus silica (TAS) diagram for the chemical classification and nomenclature of the studied rocks (after Le Bas *et al.*, 1986). Subalkaline versus alkaline series boundary (dotted lines) are from Rickwood (1989). Limits for quartz *(Qtz)* and nepheline *(Ne)* normative, and hypersthene normative *(Hy)* rocks are from Middlemost (1991). Rocks plotting into fields 4 and 6 named hawaiite and mugearite respectively according to Le Bas *et al.* (1986).

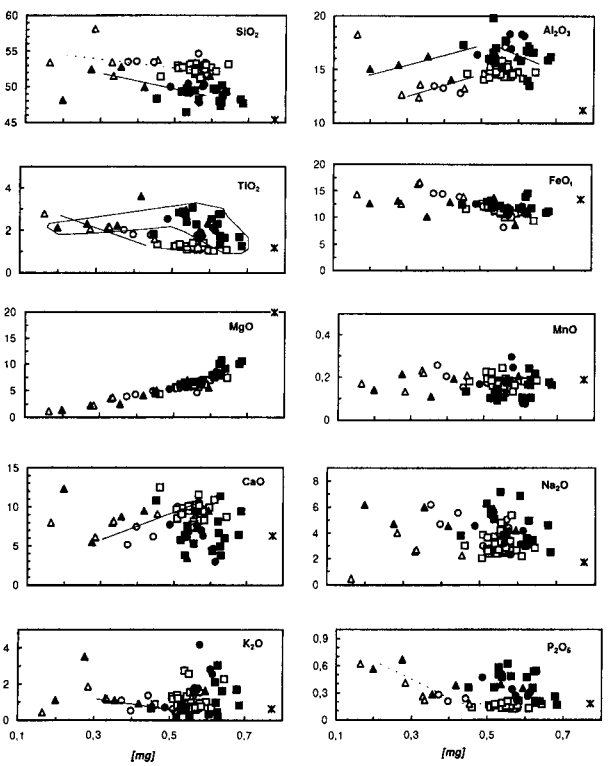

Fig. 3.—Major element variations (oxides calculated on an anhydrous basis) versus *[mg]* values. *[mg]* calculation is indicated in table 1. Same symbols as in figure 2.

tes (1 to 1.5% and 0.1 to 0.2%), and these elements exhibit a negative correlation with *[mg]*. Nevertheless TiO_2 has a contrasted behaviour in the pegmatoidal facies: in the first group, TiO_2 clearly increases with differentiation, whereas in the second group TiO_2 content decreases for *[mg]* values less than 0.4-0.5. This decrease can be explained as a consequence of the previous crystallization of high-Ti clinopyroxenes in these *ophites*. High P_2O_5, contents in the pegmatoidal facies are due to an increase of the proportion of modal apatite. MnO exhibits small variations in both groups (within the range 0.1-0.3), and shows a slight negative correlation with *[mg]*. The differentiated rocks have high FeO_{tot} which, in both groups, exhibit a negative correlation with *[mg]*.

Trace element variations with respect to *[mg]* values are presented in figure 4. Scatter in Ba, Rb and Sr contents may be a consequence of their high mobility during secondary alteration and low-grade metamorphic processes (Smith and Smith, 1976; Dickin and Jones, 1983; Dostal and Strong, 1983; Merriman *et al.*, 1986, among others), with more dispersed values in rocks with higher L.O.I. contents. Zr, Nb, Y, Th, Hf and REE are more immobile during secondary processes (Ludden *et al.*, 1982; Merriman *et al.*, 1986), and show a good negative correlation with magmatic differentiation. However, Zr and Y show more scattered patterns in the post-

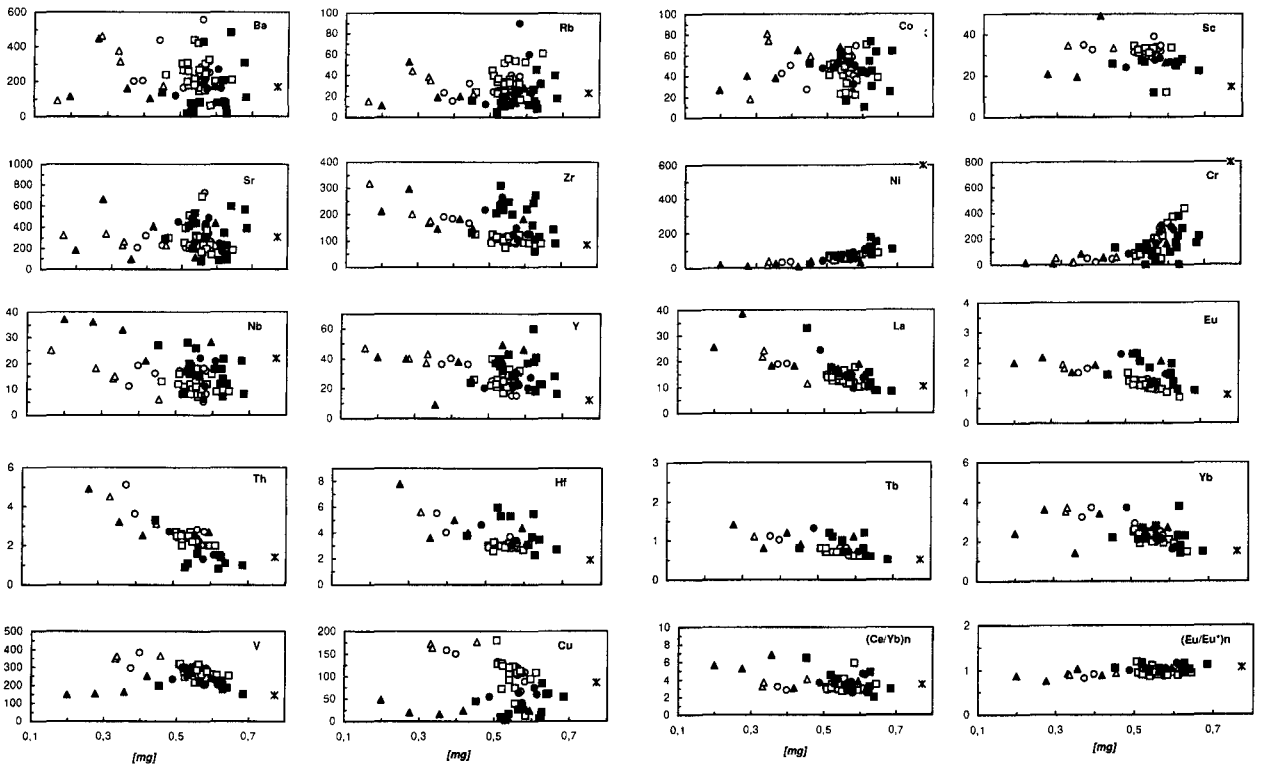

Fig. 4.—Trace element variations versus *[mg]* values. Same symbols as in figure 2.

Triassic group than in the Triassic group. Transition elements (Cu, V, Sc, Ni, Cr) show rather less scattering, except for Co. In the post-Triassic rocks, V exhibits differentiation trend similar to that of TiO_2, with concentrations increasing when differentiation decreases (up to *[mg]* values close to 0.5) and decreasing after this value. Cu contents increase with decreasing *[mg]* values in the Triassic group. This «incompatible» behaviour of Cu was considered as characteristic of continental tholeiite suites (Dupuy and Dostal, 1984). In the post-Triassic rocks, Cu contents decrease with magmatic differentiation, and has therefore a compatible behaviour.

REE abundances increase with decreasing *[mg]* (fig. 4). No variation between LREE and HREE abundances (expressed as $(Ce/Yb)_n$) and *[mg]* value is observed in the Triassic *ophites*. In the post-Triassic rocks, a slight increase of the LREE is observed in the most differentiated rocks. A slightly positive trend is observed between $(Eu/Eu^*)_n$ and *[mg]* in both groups, in accordance with the crystallization of less calcic plagioclase in the more differentiated rocks.

Variations in trace element abundances are also shown on multi-element diagram (fig. 5), normalized to N-type MORB (Pearce, 1982). Mean values and the total variation in the Triassic and post-Triassic *ophites* are shown for the three petrographic facies defined earlier. Both groups are enriched in Sr, K, Ba, Rb, Th, Nb and Ce, with higher contents in K, Rb, Ba, Th and lower values in Nb and Ce in the Triassic than in the post-Triassic rocks. In both groups, elements from P to Sc have concentrations similar to N-MORB, even if their abundances are slightly higher in the post-Triassic rocks. Slight differences exist in the patterns of the chilled margin and central facies in both types of *ophites*. Larger variations can be observed when comparing the central facies and pegmatoids: incompatible elements increase and Cr decreases. The opposite behaviour is observed in the picritic dolerite. Enrichment in Ba, Rb, Th, Sr and LREE and a decrease in Nb with respect to the N-MORB values as observed in the Triassic group is characteristic of continental tholeiites.

REE diagrams of the mean values in both *ophite* groups are shown in figure 6. Only slight differences are observed: the post-Triassic group has MREE and $(La(Yb)_n$ values higher than those of the Triassic group. In general, the *ophites* are enriched in LREE with mean $(La/Yb)_n$ values ranging from 3.7 to 4.2 for the Triassic group and 4.4 to 4.8 for the post-Triassic, and $(La/Sm)_n$ ratio ranging between

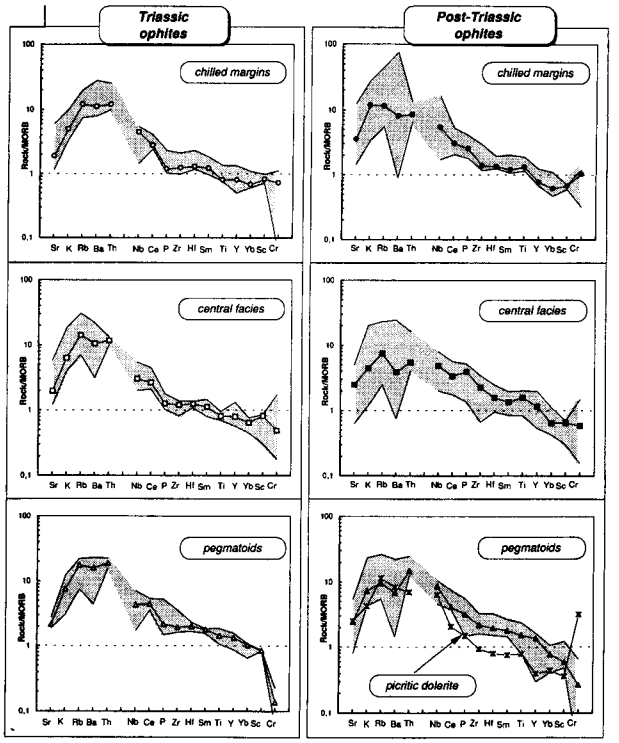

Fig. 5.—Pearce (1982) multi-element diagram of basalts from the Betic Cordillera normalised to normal MORB. For each facies, mean values and ranges (shadow areas) are plotted.

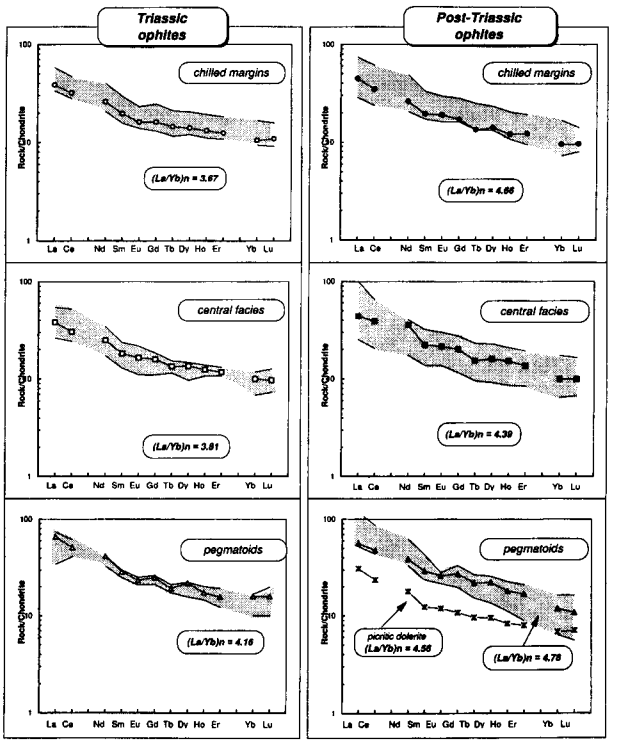

Fig. 6.—Chondrite-normalised REE patterns (values for chondrite according to Nakamura, 1974) for the mean and range values of the different petrographic facies. Mean $(La/Yb)_n$ values for each petrographic facies are indicated.

2.0 to 2.3 in the first group and 1.9 to 2.3 for the second. All samples plotted in the chondrite-normalized REE plot have approximately parallel patterns, and their $(LREE/HREE)_n$ ratios can be considered as typical of continental tholeiites and transitional basalts (Siders and Elliot, 1985, among others).

Geodynamic setting

A number of diagrams based on the geochemical composition are classically used to identify the tectonic setting of ancient basalts. A useful discriminant diagram for this purpose is the Th:Hf/3:Ta (fig. 7) of Wood (1980). On this diagram, the Triassic *ophites* plot mainly in the field of the calc-alkaline destructive margin basalts (field D2), with some points falling in the field of within-plate basalts (field C). The post-Triassic *ophites* are scattered into the fields of the enriched MORB, tholeiitic within plate basalts and alkaline within-plate basalts (fields B and C, respectively). It is interesting to note that the Triassic *ophites* follow the crustal contamination trend proposed by Wood (1980). According to this author, the Th:Hf:Ta ratios are sensitive to continental contamination processes. Thus, basaltic magmas contaminated with materials belonging to the upper continental crust would be richer in Th, and with high Th/Ta ratios. The higher Tr contents of the Triassic *ophites* can be related to a thicker crust during the first extensional stages. This point will be discussed in more detail in the end of this paper.

Geochemical affinity of the *ophites*

The chemical affinity of these basic rocks can be established from the chemistry of their igneous clinopyroxenes as well as from their whole-rock geochemistry. In the Triassic *ophites,* low Ti and Ca contents of the clinopyroxene, together with the presence of pigeonite and orthopyroxene, are typical of tholeiitic basalts. On the other hand, in the post-Triassic *ophites,* the higher Ti and Ca contents of the clinopyroxenes are indicative of a more alkaline affinity (Morata and Puga, 1993).

Certain trace element ratios are useful to constrain the geochemical affinity of these basic rocks. All the Triassic *ophites* have a Ti/V ratio lower than

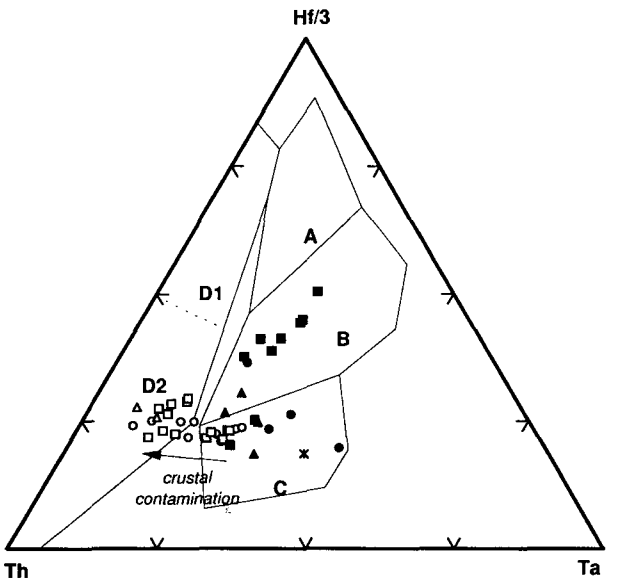

Fig. 7.—Th:Hf/3:Ta discriminant diagram (Wood, 1980). A = N-MORB; B = E-MORB and tholeiitic within-plate basalts; C = alkaline within-plate basalts; D1 = island-arc tholeiites; D2 = calc-alkaline basalts. Arrow shows the crustal contamination trend if the contaminant belongs to the upper continental crust (Wood, 1980). Same symbols as in figure 2. As Ta concentrations are lower than the detection limit. Ta contents were calculated using a Nb/Ta = 16 ratio (*c.f.* Wood *et al.*, 1979).

50, whereas in the post-Triassic *ophites* this ratio is close to or higher than 50. These values argue with the limit proposed by Shervais (1982) to discriminate between tholeiitic and alkaline basalts. On the other hand, the Nb/Y ratio (Winchester and Floyd, 1976, 1977) is considered as a good parameter to discriminate tholeiitic and alkaline basaltic rocks. Pearce (1982) concluded that rocks with Nb/Y ratios higher than 1.0 have an alkaline affinity, whereas those with Nb/Y ratios lower than 0.5 have a tholeiitic affinity; ratios between 0.5 and 1 characterize transitional affinity. Nb/Y ratio ranges between 0.2 to 1.2 (mean = 0.4) for the Triassic group, whereas for the post-Triassic rocks, its extreme values are between 0.2 and 3.7 (mean = 0.6). These Nb/Y ratios are independent of the degree of evolution, but could be affected by secondary processes such as low-grade metamorphism. Higher contents of Ti, P, Zr and Hf (fig. 5) and LREE (fig. 6) in the post-Triassic *ophites* (fig. 5) are also in agreement with their more alkaline affinity.

In summary, according to the clinopyroxene chemistry and whole-rock geochemical signatures, the Triassic *ophites,* in which orthopyroxene is present, have a **tholeiitic affinity,** whereas the post-Triassic *ophites,* which contain olivine, have a **transitional to alkaline affinity.**

Discussion and Conclusions

During the Triassic and Jurassic, basic magmatic activity intruded in the Triassic evaporitic formations of the External Zones of the Betic Cordilleras. Geochemical, radiometric ages and field data enable us to conclude that this magmatism began in the Late Triassic with a tholeiitic signature, and was followed by transitional-alkaline subvolcanic bodies.

Low Cr, Ni, and *[mg]* values in both magmatic groups indicate the absence of true primitive liquids. Moreover *[mg]* values close to 0.5-0.7 are typical of continental basalts which have experienced fractional crystallization (Cox, 1980; Dupuy and Dostal, 1984; Bellieni *et al.*, 1984). Variations in major and trace elements are consistent with low-pressure crystallization of clinopyroxene and plagioclase. The influence of orthopyroxene and olivine fractionation is reflected in the Cr and Ni contents, respectively. A narrow range in SiO_2 is typical of continental basalt magmatism, despite the large volumes of magma involved in this process (Bertrand, 1991).

Some important differences have been identified between the two rock types and concern mainly TiO_2, P_2O_5, Th, Nb, Zr, Cu. The use of various diagrams for the geodynamic discrimination of paleobasalts (*e.g.* fig. 7) have shown that both of *ophites* have a geochemical signature characteristic of continental intraplate magmatism. High Th and low Nb contents in the Triassic magmatism (fig. 5) could be a consequence of crustal contamination of mantle-derived melts during their ascent throught the crust, prior to their final emplacement into the Triassic sediments. Using major and trace element data, Puga *et al.* (1989) have shown chemical patterns indicative of granitoid contamination during the *ophite* ascent through the continental crust. Moreover, the presence of metapelitic xenoliths and xenocrysts in some post-Triassic *ophites* (Morata and Puga, 1992) indicates, that crustal contamination must have played a crucial role in their petrogenetic evolution.

The different chemical signatures of the Triassic and post-Triassic magmatism could be a consequence of different tectonic regimes during the emplacement of the magmas. According to the estimated age of the *ophites,* at the beginning of the extensional event, the continental crust would have been thicker. Under these conditions, continental contamination could have operated, resulting in relatively low Nb and high Th contents. Crustal contamination can also explain the production of SiO_2-rich melts, in which orthopyroxene and pigeonite crystallize. In the case of post-Triassic magmatism, occu-

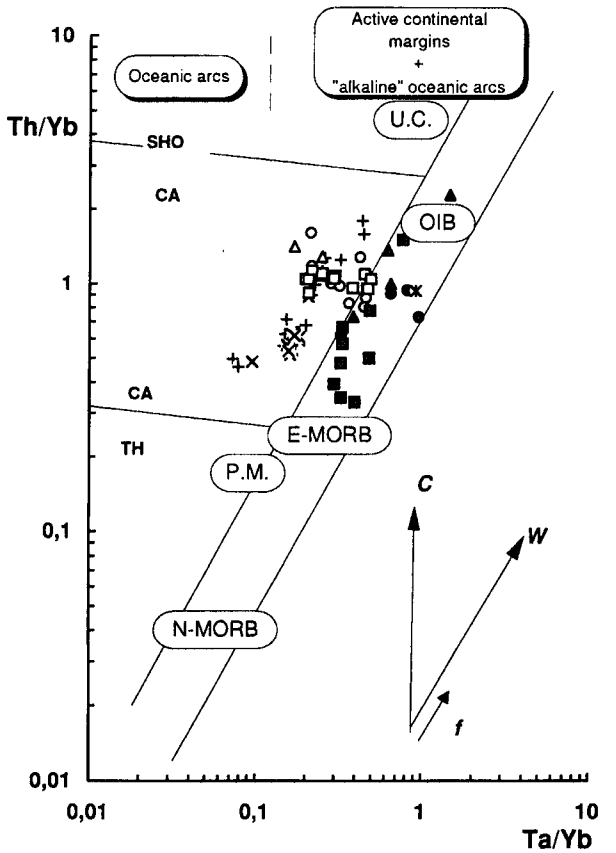

Fig. 8.—Ta/Yb *vs* Th/Yb diagram in which mid-ocean ridge and within-plate volcanic rocks plot along the diagonal band. *C* indicates continental contamination trend, and *W* mantellic enrichment. Th/Yb and Ta/Yb increase due to fractional crystallisation according to *f* (after Pearce, 1982, 1983). SHO = shoshonitic series; CA = calc-alkaline series; TH = tholeiitic series. U.C. = average composition of the upper continental crust (after Taylor and McLeannan, 1985). Primitive mantle (P.M.), N-MORB, E-MORB and OIB values from Sun and McDonough (1989). Tholeiitic dolerites from Northern Morocco (Bertrand, 1991) and Pyrenean ophites (Béziat *et al.*, 1991) are respectively plotted as (+) and (x) for comparison. Ta calculated as in figure 7.

rring in a well established extensional regime evolving towards oceanic conditions, the basalts are less contaminated, allowing the eruption of more primitive olivine basalts. On the Th/Yb versus Ta/Yb diagram (fig. 8) Triassic rocks plot outside the mantle array, probably due to Th enrichment through crustal contamination, whereas the post-Triassic magmatism plots along the mantle array, with an evolution in accordance with fractional crystallization of within-plate basalts. In this last magmatism, chemical evidences of crustal contamination are restricted to some areas in which xenoliths and xenocrysts are present. In fact, in the MORB normalized diagrams (fig. 5), the enrichment in Th (Ba, Rb, Sr) and LREE and decrease in Nb in the Triassic *ophites* can be interpreted in terms of crustal contamination

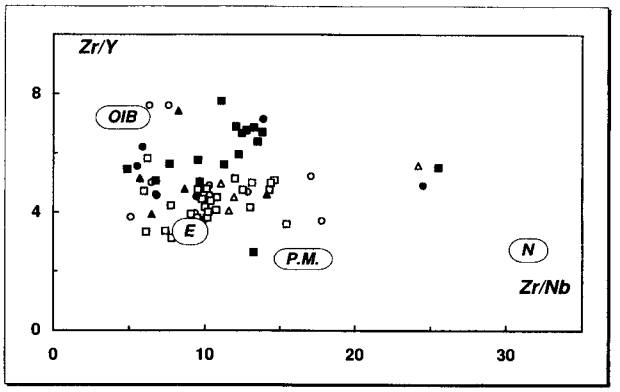

Fig. 9.—Zr/Y *vs* Zr/Nb diagram. E = E-MORB, N = N-MORB, P.M. = primordial mantle and OIB values from Sun and McDonough (1989). Symbols as in figure 2.

(Dupuy and Dostal, 1984; Dostal *et al.*, 1986; Thompson *et al.*, 1984), or as a consequence of their origin from an enriched subcontinental mantle source (Hawkesworth *et al.*, 1983; Menzies *et al*, 1983, among others).

Thus, another possible genetic factor controlling the chemical differences recorded by these basalts is a different mantle source. Both magmatisms (Triassic and post-Triassic) have $(La/Ce)_n > 1$ indicating an origin from an enriched mantle source (Marcelot *et al.*, 1989). But higher Th/Nb and lower Zr/Sm ratios in the Triassic magmatism could evidence some differences in their original mantle source. In this sense, the Zr/Nb *vs* Zr/Y plot (fig. 9) also reflects important differences. Both magmatisms plot between the extreme OIB and E-MORB poles, having the post-Triassic magmatism more similitude with the OIB end-member. On the other hand $(La/Nb) < 1.5$ for both magmatism is indicative of an asthenospheric source (Thompson and Morrison, 1988), but higher La/Nb ratios in the Triassic magmatism could indicate a lithospheric (mantellic?, crustal?) component. Also, higher Ba/Zr values in the Triassic magmatism (in spite of the Ba secondary mobility) could indicate, according to Fitton *et al.* (1995), a greater lithospheric component.

In conclusion, multiple factors (magma source, crustal contamination, primary differentiation and secondary alteration) must contribute to the final bulk geochemical signature and it is difficult to elucidate the role of each one. This Mesozoic magmatism is related to the geodynamic evolution of the South-Iberian passive margin in connection with the opening of the North Atlantic. Its chemical characteristics suggest a progressive increase of the extension of the continental crust from the Triassic to the Jurassic, characterized by crustal thinning and rela-

ted magmatism. This magmatism, generated from an enriched mantellic source, evolved from tholeiitic to transitional-alkaline, with a decreasing influence of continental crustal contamination and an increasing influence of an asthenospheric mantle component. According to this model, the tholeiitic signature of the Triassic magmatism could be a consequence of their higher lithospheric contamination during their petrogenetic evolution.

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